

QUARK MATTER SYMMETRY ENERGY AND QUARK STARS

PENG-CHENG CHU¹, LIE-WEN CHEN^{*1,2}

¹ INPAC, Department of Physics and Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai 200240, China and

² Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China
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ABSTRACT

We extend the confined-density-dependent-mass model to include isospin dependence of the equivalent quark mass. Within the confined-isospin-density-dependent-mass model, we study the quark matter symmetry energy, the stability of strange quark matter, and the properties of quark stars. We find that including isospin dependence of the equivalent quark mass can significantly enhance the quark matter symmetry energy and stiffen strange quark matter. The recently discovered large mass pulsar PSR J1614-2230 with a mass of $1.97 \pm 0.04 M_{\odot}$ can be well described by a quark star if the equivalent quark mass is strongly isospin dependent, indicating that the quark matter symmetry energy might be much stronger than the nuclear matter symmetry energy.

Subject headings: dense matter - equation of state - stars: neutron

1. INTRODUCTION

One of fundamental issues in contemporary nuclear physics, astrophysics, and cosmology is to investigate the properties of strong interaction matter, especially its equation of state (EOS), which plays a central role in understanding the nuclear structures and reactions, many critical issues in astrophysics, and the matter state at early universe. Quantum chromodynamics (QCD) is believed to be the fundamental theory for the strong interaction. Although the perturbative QCD (pQCD) has achieved impressive success in describing high energy processes, the direct application of QCD to lower energy phenomena remains a big challenge in the community due to the complicated non-perturbative feature of QCD (Fukushima & Hatsuda 2011). The *ab initio* lattice QCD (LQCD) numerical Monte Carlo calculations provide a solid basis for our knowledge of strong interaction matter at finite-temperature regime with zero baryon density (baryon chemical potential). However, the regime of finite baryon density is still inaccessible by Monte Carlo because of the Fermion sign problem (Barbour et al. 1986).

In terrestrial laboratory, heavy ion collisions (HIC's) provide a unique tool to explore the properties of strong interaction matter. The experiments of high energy HIC's performed (or being performed) in the Relativistic Heavy Ion Collider (RHIC) at BNL and the Large Hadron Collider (LHC) at CERN have revealed many interesting features of strong interaction matter at zero baryon density and high temperature. Instead of the original picture of a hot ideal gas of non-interacting deconfined quarks and gluons at zero baryon density and high temperature, the experimental data support a new picture that quarks and gluons form a strongly interacting system, just like a perfect liquid, in which non-perturbative physics plays an important role (Tang 2009). On the other hand, the properties of strong interaction matter at higher baryon density regions can

be explored by the beam-energy scan program at RHIC which aims to give a detailed picture of QCD phase structure, especially to locate the so-called QCD critical point (Stephanov et al. 1998). Knowledge of high baryon density regions can be further complemented by future experiments planned in the Facility for Antiproton and Ion Research (FAIR) at GSI and the Nuclotron-based Ion Collider Facility (NICA) at JINR.

In nature, the compact stars provide another way to explore the properties of strong interaction matter at high baryon density (and low temperature). Neutron stars (NS's) have been shown to provide natural testing grounds of our knowledge about the EOS of neutron-rich nuclear matter (Lattimer & Prakash 2004; Steiner et al. 2005). In the interior (or core) of NS's, there may exist hyperons, meson condensations, and even quark matter. Theoretically, NS's may be converted to (strange) quark stars (QS's) (Bombaci et al. 2004; Staff et al. 2007; Herzog & Ropke 2011), which is made purely of absolutely stable deconfined *u*, *d*, *s* quark matter (with some leptons), i.e., strange quark matter (SQM). Although most of observations related to compact stars can be explained by the conventional NS models, the QS hypothesis cannot be conclusively ruled out. One important feature of QS's is that for a fixed mass, QS's have smaller radii than NS's (Kapoor and Shukre 2001). It has been argued (Weber 2005) that the unusual small radii exacted from observational data support that the compact objects SAX J1808.4C3658, 4U 1728C34, 4U 1820C30, RX J1856.5C3754 and Her X-1 are QS's rather than NS's. The possible existence of QS's is one of the most intriguing aspects of modern astrophysics and has important implications for astrophysics and the strong interaction physics, especially the properties of SQM which essentially determine the structure of QS's (Ivanenko & Kurdgelaidze 1969; Itoh 1970; Bodmer 1971; Witten 1984; Farhi & Jaffe 1984; Alcock et al. 1986; Weber 2005).

The EOS of dense quark matter is usually soft due to the asymptotic freedom of QCD for quark-quark interactions at extremely high density. In addition, the

* Corresponding author, email: lwchen@sjtu.edu.cn

EOS of SQM will be further soften due to the addition of s quark which contributes a new degree of freedom. Therefore, most of quark matter models predict relatively smaller maximum mass of QS's. Recently, by using the general relativistic Shapiro delay, the mass of PSR J1614-2230 was precisely measured to be $1.97 \pm 0.04 M_\odot$ (Demorest et al. 2010), which gives the new record of the maximum mass of pulsars. This high mass seems to rule out conventional QS models (whose EOS's are soft), although some other models of pulsar-like stars with quark matter can still describe the large mass pulsar (Alford & Reddy 2003; Baldo et al. 2003; Ruster & Rischke 2004; Alford et al. 2005, 2007; Klähn et al. 2007; Ippolito et al. 2008; Lai & Xu 2011; Weissenborn et al. 2011; de Avellar et al. 2000; Bonanno & Sedrakian 2012). All these models seem to indicate that to obtain a large mass (about $2M_\odot$) pulsar-like star with quark matter, the interaction between quarks should be strong, remarkably consistent with the finding in high energy HIC's that quarks and gluons form a strongly interacting system.

In QS's, the u - d quark asymmetry (isospin asymmetry) could be large, and thus the isovector properties of SQM may play an important role. Furthermore, the quark matter formed in high energy HIC's at RHIC/LHC (and future FAIR/NICA) generally also has unequal u and d (\bar{u} and \bar{d}) quark numbers, i.e., it is isospin asymmetric. In recent years, some interesting features of QCD phase diagram at finite isospin have been revealed based on LQCD and some phenomenological models (Son & Stephanov 2001; Frank et al. 2003; Toublan & Kogut 2003; Kogut & Sinclair 2004; He & Zhuang 2005; He et al. 2005; Di Toro et al. 2006; Zhang & Liu 2007; Pagliara & Schaffner-Bielich 2010; Shao et al. 2012). These studies are all related to the isovector properties of quark matter, which is poorly known, especially at finite baryon density. Therefore, it is of great interest and critical importance to explore the isovector properties of quark matter, which is useful for understanding the properties of QS's, the isospin dependence of hadron-quark phase transition and QCD phase diagram, and the isospin effects of partonic dynamics in high energy HIC's.

QS's provide excellent astrophysical laboratory to explore the isovector properties of quark matter at high baryon density. In the present work, by extending the confined-density-dependent-mass (CDDM) model to include isospin dependence of the equivalent quark mass, we investigate the quark matter symmetry energy and the properties of QS's. We find that, although the maximum mass of QS's within the original CDDM model is significantly smaller than $2M_\odot$, a strong quark matter symmetry energy introduced in the extended CDDM model can stiffen SQM and thus the large mass pulsar PSR J1614-2230 with a mass of $1.97 \pm 0.04 M_\odot$ can be well described by a QS.

2. THE THEORETICAL FORMULISM

2.1. The confined isospin and density dependent mass model

According to the Bodmer-Witten-Terazawa hypothesis (Witten 1984; Weber 2005), SQM might be the true ground state of QCD matter (i.e., the strong interaction

matter) and is absolutely stable. Furthermore, Farhi and Jaffe found that SQM is stable near nuclear saturation density for large model parameter space (Farhi & Jaffe 1984). The properties of SQM cannot be calculated directly from pQCD or LQCD, because SQM has finite baryon density and its energy scale is not very high. To understand the properties of SQM, people have builded some QCD-inspired effective phenomenological models, such as the MIT bag model (Chodos et al. 1974; Alford et al. 2005; Weber 2005), the Nambu-Jona-Lasinio (NJL) model (Rehberget al. 1996; Han et al. 2001; Ruster & Rischke 2004; Menezes et al. 2006), the pQCD approach (Freedman & McLerran 1977, 1978; Kurkela et al. 2010), and the Dyson-Schwinger approach (Roberts & Williams 1994; Zong et al. 2005; Qin et al. 2011; Li et al. 2011a). At extremely high baryon density, SQM could be in color-flavor-locked (CFL) state (Rajagopal & Wilczek 2000) in which the current masses of u , d and s quarks become less important compared with their chemical potentials and the quarks have equal fractions with the lepton number density being zero according to charge neutrality.

In quark matter models, one of most important things is to treat quark confinement. The MIT bag model (Farhi & Jaffe 1984; Alcock et al. 1986) and its density dependent versions provide a popular way to treat quark confinement. Another popular way to treat quark confinement is to vary the interaction part of quark mass, such as the CDDM model (Fowler et al. 1981; Chakrabarty et al. 1989; Chakrabarty 1991, 1993, 1996; Benvenuto et al. 1995; Peng et al. 1999; Peng et al. 2000; Peng et al. 2008; Zhang & Su 2002; Wen et al. 2005; Mao et al. 2006; Wu et al. 2008; Yin & Su 2008) and the quasi-particle model (Schertler et al. 1997, 1998; Peshier et al. 2000; Horvath & Lugones 2004; Alford et al. 2007). In the present work, we focus on the CDDM model in which the quark confinement is modeled by the density dependence of the interaction part of quark mass, i.e., the density dependent equivalent quark mass.

In the CDDM model, the (equivalent) quark mass in quark matter with baryon density n_B is usually parameterized as

$$m_q = m_{q0} + m_I = m_{q0} + \frac{D}{n_B^z}, \quad (1)$$

where m_{q0} is the quark current mass and $m_I = \frac{D}{n_B^z}$ reflects the quark interactions in quark matter which is assumed to be density dependent, z is the quark mass scaling parameter, and D is a parameter determined by stability arguments of SQM. In the original CDDM model used to study two-flavor u - d quark matter (Fowler et al. 1981), an inversely linear quark mass scaling, i.e., $z = 1$ was assumed and the parameter D was taken to be 3 times the famous MIT bag constant. The CDDM model was later extended to include s quarks to investigate the properties of SQM (Chakrabarty et al. 1989; Chakrabarty 1991, 1993, 1996; Benvenuto et al. 1995). Obviously, the CDDM model satisfies two basic features of QCD, i.e., the asymptotic freedom and quark confinement through density dependence of the equivalent quark mass, i.e., $\lim_{n_B \rightarrow \infty} m_I = 0$ and $\lim_{n_B \rightarrow 0} m_I = \infty$. For two-flavor u - d quark matter, the chiral symmetry is re-

stored at high density due to $\lim_{n_B \rightarrow \infty} m_q = 0$ if the current masses of u and d quarks are neglected.

The density dependence of the interaction part of the quark mass, i.e., $m_I = \frac{D}{n_B^z}$ is phenomenological in the CDDM model, and in principle it should be determined by non-perturbative QCD calculations. Instead of the inversely linear density dependence for m_I which is based on the bag model argument, a quark mass scaling parameter of $z = 1/3$ was derived based on the in-medium chiral condensates and linear confinement (Peng et al. 1999) and has been widely used for exploring the properties of SQM and QS's since then (Lugones & Horvath 2003; Zheng et al. 2004; Peng et al. 2006; Wen et al. 2007; Peng et al. 2008; Li et al. 2011b). In a recent work (Li et al. 2010), Li A. et al. investigated the stability of SQM and the properties of the corresponding QS's for a wide range of quark mass scalings. Their results indicate that the resulting maximum mass always lies between $1.5M_\odot$ and $1.8M_\odot$ for all the scalings chosen there. This implies that the large mass pulsar PSR J1614-2230 with a mass of $1.97 \pm 0.04M_\odot$, cannot be a QS within the CDDM model. In particular, the maximum mass with scaling parameter $z = 1/3$ is only about $1.65M_\odot$, significantly less than $1.97 \pm 0.04M_\odot$.

Physically, the quark-quark effective interaction in quark matter should be isospin dependent. Based on chiral perturbation theory, it has been shown recently (Kaiser & Weise 2009) that the in-medium density dependent chiral condensates are significantly dependent on the isospin. The isospin dependence of the in-medium chiral condensates can also be seen from the QCD sum rules (Drukarev et al. 2004; Jeong & Lee 2012). In addition, the quark-quark interaction in quark matter will be screened due to pair creation and infrared divergence and the (Debye) screening length is also isospin dependent (Dey et al. 1998). These features imply that the equivalent quark mass in Eq. (1) should be isospin dependent which is neglected in the CDDM model. However, the detailed form of isospin dependence of the equivalent quark mass is unknown, and in principle it should be determined by non-perturbative QCD calculations. In the present work, we extend the CDDM model to include the isospin dependence of the quark-quark effective interactions by assuming phenomenologically the following form for the equivalent quark mass in isospin asymmetric quark matter with isospin asymmetry δ , i.e.,

$$\begin{aligned} m_q &= m_{q_0} + m_I + m_{iso} \\ &= m_{q_0} + \frac{D}{n_B^{1/3}} - \tau_q \delta D_I n_B^\alpha e^{-\beta n_B}, \end{aligned} \quad (2)$$

where D_I , α , and β are parameters determining isospin dependence of the quark-quark effective interactions in quark matter, τ_q is the isospin quantum number of quarks, and here we set $\tau_q = 1$ for $q = u$ (u quarks), $\tau_q = -1$ for $q = d$ (d quarks), and $\tau_q = 0$ for $q = s$ (s quarks). The isospin asymmetry is defined as

$$\delta = 3 \frac{n_d - n_u}{n_d + n_u}, \quad (3)$$

which equals to $-n_3/n_B$ with the isospin density $n_3 = n_u - n_d$ and $n_B = (n_u + n_d)/3$ for two-flavor u - d quark matter. The above definition of δ for quark matter has been extensively used in the literature (Di Toro et al.

2006; Pagliara & Schaffner-Bielich 2010; Di Toro et al. 2010; Shao et al. 2012). We note that one has $\delta = 1$ (-1) for quark matter converted by pure neutron (proton) matter according to the nucleon constituent quark structure, consistent with the conventional definition for nuclear matter, i.e., $\frac{\rho_n - \rho_p}{\rho_n + \rho_p} = -n_3/n_B$. In Eq. (2), the parameters α and β should be positive so that we have $\lim_{n_B \rightarrow \infty} m_{iso} = 0$ and $\lim_{n_B \rightarrow 0} m_{iso} = 0$ to respect the asymptotic freedom and quark confinement. In addition, in this work, we set $z = 1/3$ since an be derived based on the in-medium chiral condensates and linear confinement (Peng et al. 1999). Obviously, in the confined isospin and density dependent mass (CDDM) model, the equivalent quark mass in Eq. (2) satisfies the exchange symmetry between u and d quarks which is required by isospin symmetry of the strong interaction. Therefore, the form of isospin dependence of the equivalent quark mass in Eq. (2) is quite general and respects the basic features of QCD.

2.2. The quark matter symmetry energy

Similarly to the case of nuclear matter (See, e.g., Li et al. 2008), the EOS of quark matter consisting of u , d , and s quarks, defined by its binding energy per baryon number, can be expanded in isospin asymmetry δ as

$$E(n_B, \delta, n_s) = E_0(n_B, n_s) + E_{\text{sym}}(n_B, n_s) \delta^2 + \mathcal{O}(\delta^4), \quad (4)$$

where $E_0(n_B, n_s) = E(n_B, \delta = 0, n_s)$ is the binding energy per baryon number in three-flavor u - d - s quark matter with equal fraction of u and d quarks; the quark matter symmetry energy $E_{\text{sym}}(n_B, n_s)$ is expressed as

$$E_{\text{sym}}(n_B, n_s) = \frac{1}{2!} \left. \frac{\partial^2 E(n_B, \delta, n_s)}{\partial \delta^2} \right|_{\delta=0}. \quad (5)$$

In Eq. (4), the absence of odd-order terms in δ is due to the exchange symmetry between u and d quarks in quark matter when one neglects the Coulomb interaction among quarks. The higher-order coefficients in δ are usually very small. Neglecting the contribution from higher-order terms in Eq. (4) leads to the empirical parabolic law, i.e., $E(n_B, \delta, n_s) \simeq E_0(n_B, n_s) + E_{\text{sym}}(n_B, n_s) \delta^2$ for the EOS of isospin asymmetric quark matter and the quark matter symmetry energy can thus be extracted approximately from the following expression

$$\begin{aligned} E_{\text{sym}}(n_B, n_s) &\simeq \frac{1}{9} [E(n_B, \delta = 3, n_s) \\ &\quad - E(n_B, \delta = 0, n_s)]. \end{aligned} \quad (6)$$

In quark matter consisting of u , d , and s quarks, the baryon number density is given by $n_B = (n_u + n_d + n_s)/3$ and the quark number density can be expressed as

$$n_i = \frac{g_i}{2\pi^2} \int_0^{\nu_i} k^2 dk = \frac{\nu_i^3}{\pi^2}, \quad (7)$$

where $g_i = 6$ is the degeneracy factor of quarks and ν_i is the Fermi momentum of different quarks ($i = u, d$, and s). Furthermore, the Fermi momenta of u and d quarks

can be expressed, respectively, as

$$\begin{aligned}\nu_u &= (1 - \delta/3)^{\frac{1}{3}}\nu, \\ \nu_d &= (1 + \delta/3)^{\frac{1}{3}}\nu,\end{aligned}\quad (8)$$

where ν is the quark Fermi momentum of symmetric u - d quark matter at quark number density $n = 2n_u = 2n_d$. The total energy density of the u - d - s quark matter can then be expressed as

$$\begin{aligned}\epsilon_{uds} &= \frac{g}{2\pi^2} \int_0^{(1-\delta/3)^{\frac{1}{3}}\nu} \sqrt{k^2 + m_u^2} k^2 dk \\ &+ \frac{g}{2\pi^2} \int_0^{(1+\delta/3)^{\frac{1}{3}}\nu} \sqrt{k^2 + m_d^2} k^2 dk \\ &+ \frac{g}{2\pi^2} \int_0^{\nu_s} \sqrt{k^2 + m_s^2} k^2 dk.\end{aligned}\quad (9)$$

Using the isospin and density dependent equivalent quark masses as in Eq. (2), we can obtain analytically the quark matter symmetry energy as

$$\begin{aligned}E_{\text{sym}}(n_B, n_s) &= \frac{1}{2} \frac{\partial^2 \epsilon_{uds}/n_B}{\partial \delta^2} \Big|_{\delta=0} \\ &= \left[\frac{\nu^2 + 18m D_I n_B^\alpha e^{-\beta n_B}}{18\sqrt{\nu^2 + m^2}} \right. \\ &\quad \left. + A + B \right] \frac{3n_B - n_s}{3n_B},\end{aligned}\quad (10)$$

with

$$\begin{aligned}A &= \frac{9m^2}{2\nu^2 \sqrt{\nu^2 + m^2}} (D_I n_B^\alpha e^{-\beta n_B})^2, \\ B &= \frac{9}{4\nu^3} \left[\nu \sqrt{\nu^2 + m^2} - 3m^2 \ln \left(\frac{\nu \sqrt{\nu^2 + m^2}}{m} \right) \right] \\ &\quad \times (D_I n_B^\alpha e^{-\beta n_B})^2,\end{aligned}\quad (11)$$

and $m = m_{u0}$ (or m_{d0}) $+\frac{D}{n_B^{1/3}}$. In the present work, we assume $m_{u0} = m_{d0} = 5.5$ MeV and $m_{s0} = 80$ MeV. In the CDDM model, the quark matter symmetry energy is reduced to

$$E_{\text{sym}}(n_B, n_s) = \frac{1}{18} \frac{\nu^2}{\sqrt{\nu^2 + m^2}} \frac{3n_B - n_s}{3n_B}. \quad (13)$$

It should be noted that the quark matter symmetry energy generally depends on the fraction of s quarks in quark matter since s quarks contribute to the baryon density n_B . For two-flavor u - d quark matter, the quark matter symmetry energy is reduced to the well-known expression, i.e., $E_{\text{sym}}(n_B) = \frac{1}{18} \frac{\nu^2}{\sqrt{\nu^2 + m^2}}$.

2.3. Properties of strange quark matter

For SQM, we assume it is neutrino-free and composed of u , d , s quarks and e^- in beta-equilibrium with electric charge neutrality. The weak beta-equilibrium condition can then be expressed as

$$\mu_u + \mu_e = \mu_d = \mu_s, \quad (14)$$

where μ_i ($i = u, d, s$ and e^-) is the chemical potential of the particles in SQM. Furthermore, the electric charge

neutrality condition can be written as

$$\frac{2}{3}n_u = \frac{1}{3}n_d + \frac{1}{3}n_s + n_e. \quad (15)$$

The chemical potential of particles in SQM can be obtained as

$$\begin{aligned}\mu_i &= \frac{d\epsilon}{dn_i} = \sqrt{\nu_i^2 + m_i^2} + \sum_j n_j \frac{\partial m_j}{\partial n_B} \frac{\partial n_B}{\partial n_i} f\left(\frac{\nu_j}{m_j}\right) \\ &\quad + \sum_j n_j \frac{\partial m_j}{\partial \delta} \frac{\partial \delta}{\partial n_i} f\left(\frac{\nu_j}{m_j}\right),\end{aligned}\quad (16)$$

with

$$f(x) = \frac{3}{2x^3} \left[x\sqrt{x^2 + 1} + \ln(x + \sqrt{x^2 + 1}) \right], \quad (17)$$

and ϵ is the total energy density of SQM. One can see clearly from Eq. (16) that the chemical potential of quarks in SQM has two additional parts compared with the case of free Fermi gas, due to the density and isospin dependence of the quark mass, respectively. In particular, the u quark chemical potential can be expressed analytically as

$$\begin{aligned}\mu_u &= \sqrt{\nu^2 + m_u^2} + \frac{1}{3} \sum_{j=u,d,s} n_j f\left(\frac{\nu_j}{m_j}\right) \\ &\quad \times \left[-\frac{D}{3n_B^{4/3}} - \tau_j D_I \delta (\alpha n_B^{\alpha-1} - \beta n_B^\alpha) e^{-\beta n_B} \right] \\ &\quad + D_I n_B^\alpha e^{-\beta n_B} \left[n_u f\left(\frac{\nu_u}{m_u}\right) - n_d f\left(\frac{\nu_d}{m_d}\right) \right] \\ &\quad \times \frac{6n_d}{(n_u + n_d)^2}.\end{aligned}\quad (18)$$

For d and s quarks, we have, respectively,

$$\begin{aligned}\mu_d &= \sqrt{\nu^2 + m_d^2} + \frac{1}{3} \sum_{j=u,d,s} n_j f\left(\frac{\nu_j}{m_j}\right) \\ &\quad \times \left[-\frac{D}{3n_B^{4/3}} - \tau_j D_I \delta (\alpha n_B^{\alpha-1} - \beta n_B^\alpha) e^{-\beta n_B} \right] \\ &\quad + D_I n_B^\alpha e^{-\beta n_B} \left[n_d f\left(\frac{\nu_d}{m_d}\right) - n_u f\left(\frac{\nu_u}{m_u}\right) \right] \\ &\quad \times \frac{6n_u}{(n_u + n_d)^2},\end{aligned}\quad (19)$$

and

$$\begin{aligned}\mu_s &= \sqrt{\nu_s^2 + m_s^2} + \frac{1}{3} \sum_{j=u,d,s} n_j f\left(\frac{\nu_j}{m_j}\right) \\ &\quad \times \left[-\frac{D}{3n_B^{4/3}} - \tau_j D_I \delta (\alpha n_B^{\alpha-1} - \beta n_B^\alpha) e^{-\beta n_B} \right].\end{aligned}\quad (20)$$

For electrons, the chemical potential can be expressed as

$$\mu_e = \sqrt{3\pi^2 \nu_e^2 + m_e^2}. \quad (21)$$

The pressure of SQM can be given by

$$\begin{aligned}
 P &= -\epsilon + \sum_{j=u,d,s,e} n_j \mu_j \\
 &= -\Omega_0 + \sum_{i,j=u,d,s,e} n_i n_j \frac{\partial m_j}{\partial n_B} \frac{\partial n_B}{\partial n_i} f\left(\frac{\nu_j}{m_j}\right) \\
 &\quad + \sum_{i,j=u,d,s,e} n_i n_j \frac{\partial m_j}{\partial \delta} \frac{\partial \delta}{\partial n_i} f\left(\frac{\nu_j}{m_j}\right), \quad (22)
 \end{aligned}$$

where $-\Omega_0$ is the free-particle contribution and Ω_0 can be expressed analytically as

$$\begin{aligned}
 \Omega_0 &= - \sum_{j=u,d,s,e} \frac{g_j}{48\pi^2} \left[\nu_j \sqrt{\nu_j^2 + m_j^2} (2\nu_j^2 - 3m_j^2) \right. \\
 &\quad \left. + 3m_j^4 \operatorname{arcsinh}\left(\frac{\nu_j}{m_j}\right) \right]. \quad (23)
 \end{aligned}$$

Because of the additional parts in the quark chemical potentials due to the density and isospin dependence of the quark mass, the pressure also has corresponding additional terms. Including such terms is important for guaranteeing the thermodynamic self-consistency of the model and the Hugenholtz-Van Hove theorem is then fulfilled (Peng et al. 1999).

3. RESULTS

3.1. The quark matter symmetry energy

In Fig. 1, we show the baryon number density dependence of the quark matter symmetry energy in the CIDD model with three typical parameter sets, i.e., DI-0, DI-300, and DI-2500. We have considered two typical cases, i.e., two-flavor u - d quark matter with $n_s = 0$ and u - d - s quark matter with $n_s = n_B$. The latter roughly corresponds to the situation inside QS's where s quarks may have equal fraction as u and d quarks. For the parameter set DI-0, we have $D_I = 0$, $\alpha = 0$, $\beta = 0$, and $D^{1/2} = 156$ MeV, which corresponds to a typical parameter set in the CDDM model. For the parameter set DI-300, we have $D_I = 300$ MeV \cdot fm $^{3\alpha}$, $\alpha = 1$, $\beta = 0.1$ fm 3 , and $D^{1/2} = 151$ MeV while $D_I = 2500$ MeV \cdot fm $^{3\alpha}$, $\alpha = 0.8$, $\beta = 0.1$ fm 3 , and $D^{1/2} = 144$ MeV for the parameter set DI-2500.

It is seen from Fig. 1 that the three parameter sets DI-0, DI-300, and DI-2500 give very different predictions for the density dependent quark matter symmetry energy, and thus the three parameter sets allow us to explore the quark matter symmetry energy effects. For comparison, we also include in Fig. 1 the nuclear matter symmetry energy from the covariant relativistic mean field (RMF) model with interaction NL $\rho\delta$ (Liu et al. 2002) which includes the isovector-scalar δ meson field and is obtained by fitting the empirical properties of asymmetric nuclear matter and describes reasonably well the binding energies and charge radii of a large number of nuclei (Gaitanos et al. 2004). Although the density dependence of the nuclear matter symmetry energy is still largely uncertainty, especially at supersaturation density (For a recent review, see, e.g., Chen 2012), the NL $\rho\delta$ result nevertheless represents a typical prediction of the nuclear matter symmetry energy. One can see that the symmetry energy values of two-flavor u - d quark

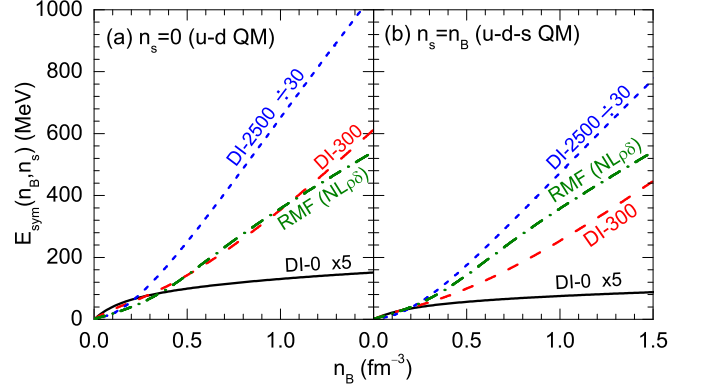


FIG. 1.— (Color online) The quark matter symmetry energy as a function of baryon number density in the CIDD model with three parameter sets, i.e., DI-0, DI-300, and DI-2500. The two-flavor u - d quark matter with $n_s = 0$ (left window) and the u - d - s quark matter with $n_s = n_B$ (right window) are considered. The nuclear matter symmetry energy from the RMF model with interaction NL $\rho\delta$ is also included for comparison. The symmetry energy values from DI-2500 have been divided by a factor of 30 while those of DI-0 have been multiplied by a factor of 5.

matter predicted by DI-300 are remarkably in agreement with those of nuclear matter with NL $\rho\delta$ while the u - d quark matter symmetry energy predicted by DI-2500 are about 50 times stronger. On the other hand, the amplitude of the quark matter symmetry energy predicted by DI-0 is much smaller than that of the nuclear matter symmetry energy. In addition, one can see from Fig. 1 that increasing s quark fraction in u - d - s quark matter reduces the quark matter symmetry energy as expected since s quarks contribute to the baryon density n_B while the symmetry energy is defined by per baryon number.

In the CIDD model, we can generally increase the quark matter symmetry energy by increasing the D_I value. It should be mentioned that when the value of D_I parameter is varied, the other three parameters α , β , and D usually need correspondingly readjustment to guarantee the stability of SQM. As we will see in the following, the three parameter sets DI-0, DI-300, and DI-2500 all satisfy the stability conditions of SQM, and thus they can be used to study the properties of SQM and QS's.

3.2. The stability of SQM

Following Farhi and Jaffe (Farhi & Jaffe 1984), the absolute stability of SQM requires that the minimum energy per baryon of SQM should be less than the minimum energy per baryon of observed stable nuclei, i.e., $M(^{56}\text{Fe})c^2/56 = 930$ MeV, and at the same time the minimum energy per baryon of the beta-equilibrium two-flavor u - d quark matter should be larger than 930 MeV to be consistent with the standard nuclear physics. These stability conditions usually put very strong constraints on the value of the parameters in quark matter models.

Figure 2 shows the energy per baryon and the corresponding pressure as a function of the baryon density for SQM and two-flavor u - d quark matter in β -equilibrium within the CIDD model with DI-0, DI-300, and DI-2500. One can see that for all the three parameter sets DI-0, DI-300, and DI-2500, the minimum energy per baryon of the beta-equilibrium two-flavor u - d quark matter is larger than 930 MeV while that of SQM is less than 930 MeV, satisfying the absolute stable conditions of SQM. Furthermore, it is seen from Fig. 2 that

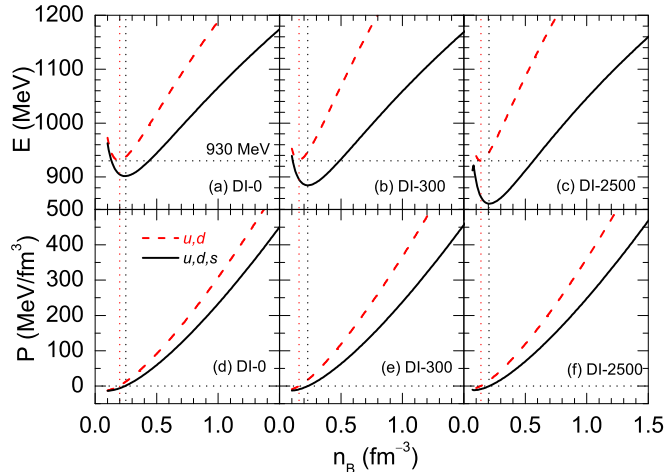


FIG. 2.— (Color online) Energy per baryon and the corresponding pressure as a function of the baryon density for SQM and two-flavor u - d quark matter in β -equilibrium within the CIDDm model with DI-0, DI-300, and DI-2500.

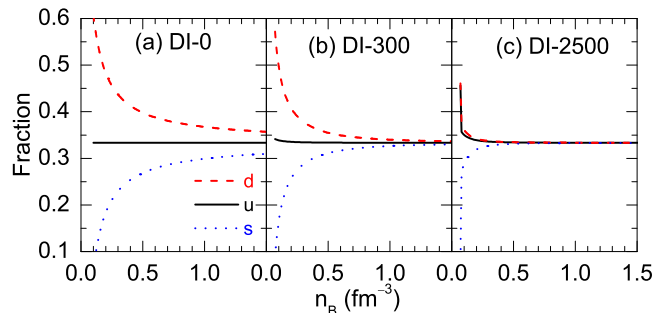


FIG. 3.— (Color online) Quark fraction as a function of the baryon density in SQM within the CIDDm model with DI-0, DI-300, and DI-2500

in all cases, the baryon density at the minimum energy per baryon is exactly the zero-pressure density, which is consistent with the requirement of thermodynamical self-consistency. In particular, we note that the zero-pressure density of SQM is 0.24 fm^{-3} , 0.23 fm^{-3} , and 0.21 fm^{-3} for DI-0, DI-300, and DI-2500, respectively, which are not so far from the nuclear matter normal density of about 0.16 fm^{-3} . Moreover, one can see from Fig. 2 that the stiffness of SQM increases with the D_I parameter (i.e., the quark matter symmetry energy). In addition, we have checked the sound speed in the quark matter based on the calculated pressure and energy density, and we find that the sound speed in all cases is less than the speed of light in vacuum, and thus satisfying the causality condition.

In Fig. 3, we show the quark fraction as a function of the baryon density in SQM within the CIDDm model with DI-0, DI-300, and DI-2500. It is interesting to see that the difference among u , d , and s quark fractions becomes smaller when the quark matter symmetry energy is increased (i.e., from DI-0 to DI-300, and then to DI-2500). When the quark matter symmetry energy is not so large (i.e., in the cases of DI-0 and DI-300), the u , d , and s quark fractions are significantly different, especially at lower baryon densities, which leads to a larger isospin asymmetry in SQM. On the other hand, a large quark matter symmetry energy (i.e., DI-

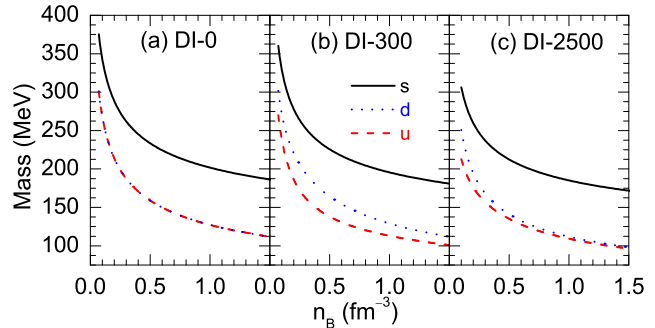


FIG. 4.— (Color online) Equivalent quark mass as a function of the baryon density in SQM within the CIDDm model with DI-0, DI-300, and DI-2500.

2500) significantly reduces the difference of u , d , and s quark fractions. In particular, for DI-2500, it is remarkable to see that the u , d , and s quark fractions become equal and approach a value of about 0.33 for $\rho_B \gtrsim 0.4 \text{ fm}^{-3}$, similar to the results from the picture of CFL state. In neutron star matter, the similar symmetry energy effect has been observed, i.e., a strong nuclear matter symmetry energy will give a larger proton fraction and thus reduce the difference between neutron and proton fractions in the beta-equilibrium neutron star matter (See, e.g., Xu et al. 2009).

Figure 4 show the equivalent quark mass as a function of the baryon density in SQM within the CIDDm model with DI-0, DI-300, and DI-2500. It is seen that in all cases, the equivalent quark mass increases drastically with decreasing baryon density, reflecting the feature of quark confinement. Furthermore, interestingly one can see a clear isospin splitting of the u and d equivalent quark masses in SQM for the parameter sets DI-300 and DI-2500, with d quarks having larger equivalent mass than u quarks. These features reflect isospin dependence of quark-quark effective interactions in isospin asymmetric quark matter in the present CIDDm model.

3.3. Quark stars

Using the EOS's of SQM as shown in Fig. 2, we can obtain the mass-radius relation of static QS's by solving the Tolman-Oppenheimer-Volkov equation. Shown in Fig. 5 is the mass-radius relation for static QS's within the CIDDm model with DI-0, DI-300, and DI-2500. Indicated by the shaded band in Fig. 5 is the latest new holder of the maximum mass of pulsars of $1.97 \pm 0.04 M_\odot$ from PSR J1614-2230 (Demorest et al. 2010). For the parameter set DI-2500, we also include in Fig. 5 the result for rotating QS's with a spin period of 3.15 ms (i.e., the measured value for PSR J1614-2230), by using the RNS code (Cook et al. 1994; Stergioulas & Friedman 1995; Komatsu et al. 1989) developed by Stergioulas (available as a public domain program at <http://www.gravity.phys.uwm.edu/rns/>). The radius value of the rotating QS's is taken at the equator.

From Fig. 5, one can see for the parameter set DI-0 which corresponds to the case of the CDDm model and has much small quark matter symmetry, the maximum mass of the static QS's is $1.65 M_\odot$ and the corresponding radius is 9.60 km. Therefore, the maximum mass with DI-0 is significantly smaller than the observed value of

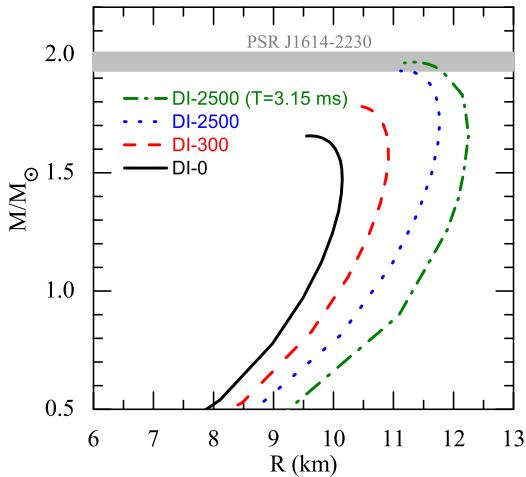


FIG. 5.— (Color online) Mass-radius relation for static quark stars within the CIDDm model with DI-0, DI-300, and DI-2500. The result for rotating quark stars with a spin period of 3.15 ms is also shown for the case of DI-2500 with the radius at the equator. The shaded band represents the latest new holder of the maximum mass of pulsars of $1.97 \pm 0.04 M_\odot$ from PSR J1614-2230 Demorest et al. (2010).

$1.97 \pm 0.04 M_\odot$ for PSR J1614-2230. For the parameter set DI-300 whose prediction of quark matter symmetry energy has almost same amplitude as the nuclear matter symmetry energy, the maximum mass of the static QS's is increased to $1.78 M_\odot$ with the corresponding radius of 10.40 km, indicating that increasing the D_I parameter (and thus the quark matter symmetry energy) in the CIDDm model can significantly enhance the maximum mass of the static QS's. The DI-2500 parameter set with $D_I = 2500 \text{ MeV} \cdot \text{fm}^{3\alpha}$ gives rise to a maximum mass of $1.93 M_\odot$ for static QS's with the corresponding radius of 11.12 km, which is consistent with the observed mass of $1.97 \pm 0.04 M_\odot$ for PSR J1614-2230 within the error bar. Furthermore, considering the rotation of QS's with a spin period of 3.15 ms as the measured value for PSR J1614-2230, we obtain the maximum mass of $1.97 M_\odot$ for rotating QS's with the corresponding radius of 11.33 km for the parameter set DI-2500, which is nicely in agreement with the observed maximum mass of $1.97 \pm 0.04 M_\odot$. Our results imply that in the CIDDm model, a larger D_I parameter (and thus a strong isospin dependence of the equivalent quark mass) is necessary to describe the observed large mass of $1.97 \pm 0.04 M_\odot$ for a QS, which means the amplitude of the quark matter symmetry energy should be much larger than that of the nuclear matter symmetry energy. These features indicate that PSR J1614-2230 could be a QS in the CIDDm model, and if PSR J1614-2230 were indeed a QS, it can put important constraint on the isovector properties of quark matter, especially the quark matter symmetry energy.

For an EOS of SQM, it is physically interesting to determine the maximum mass of QS's at the maximum rotation frequency constrained by the mass shedding and the secular instability with respect to axisymmetric perturbations, which essentially corresponds to the maximum mass of rotating QS's that the EOS can support. The maximum angular frequency Ω_{max} of a rotating QS can be obtained from its static mass M_\odot^{stat} and radius $R_{M_\odot}^{stat}$ by using the empirical formula proposed by (Gourgoulhon et al. 1999), i.e., $\Omega_{max} =$

TABLE 1
THE MAXIMUM MASS, THE CORRESPONDING RADIUS AND CENTRAL BARYON NUMBER DENSITY OF THE STATIC QUARK STARS, THE MAXIMUM ROTATIONAL FREQUENCY f_{max} FOR MAXIMUM-MASS STATIC QUARK STARS AS WELL AS THE CORRESPONDING GRAVITATIONAL MASS AND EQUATORIAL RADIUS AT f_{max} , WITHIN THE CIDDm MODEL WITH DI-0, DI-300, AND DI-2500.

	DI-0	DI-300	DI-2500
$M/M_\odot(\text{static})$	1.65	1.78	1.93
$R(\text{km})(\text{static})$	9.60	10.40	11.12
Central density(fm^{-3})	1.31	1.11	1.06
f_{max} (Hz)	1680	1547	1458
M/M_\odot (at f_{max})	1.78	2.12	2.43
$R(\text{km})$ (equator at f_{max})	9.93	11.6	14.2

$$7730 (M_\odot^{stat}/M_\odot)^{1/2} (R_{M_\odot}^{stat}/10\text{km})^{-3/2} \text{ rad} \cdot \text{s}^{-1}.$$

In Table 1, we list the maximum rotational frequency f_{max} for maximum-mass static QS's as well as the corresponding gravitational mass and equatorial radius at f_{max} , within the CIDDm model with DI-0, DI-300, and DI-2500. For completeness, we also include in Table 1 the results for the maximum mass, the corresponding radius and central baryon number density of the static QS's. From Table 1, one can see the maximum rotational frequency f_{max} decreases with D_I while the corresponding mass and equatorial radius increase with D_I . In particular, for the parameter set DI-2500, we obtain $f_{max} = 1458 \text{ Hz}$, and the corresponding mass is $2.43 M_\odot$ with radius of 14.2 km, which essentially corresponds to the maximum mass configuration of rotating QS's that the parameter set DI-2500 can support.

4. CONCLUSION

We extend the confined-density-dependent-mass model in which the quark confinement is modeled by the density-dependent quark masses to include isospin dependence of the quark mass. Within the confined-isospin-density-dependent-mass model, we study the quark matter symmetry energy, the stability of strange quark matter, and the properties of quark stars. We find that including isospin dependence of the quark mass can significantly change the quark matter symmetry energy, and the recently discovered new holder of pulsar maximum mass, i.e., the millisecond PSR J1614-2230 of $1.97 \pm 0.04 M_\odot$, can be well described by a quark star with a strong isospin dependence of the quark mass, corresponding to a strong quark matter symmetry energy. Our results indicate that if PSR J1614-2230 were indeed a quark star, it can put important constraint on the isovector properties of quark matter, especially the quark matter symmetry energy. In particular, we find that PSR J1614-2230 can be well described by a quark star within the confined-isospin-density-dependent-mass model with the parameter set DI-2500, indicating that the quark matter symmetry energy might be much stronger than the nuclear matter symmetry energy.

In the present work, we have mainly focused on the quark matter symmetry energy and the properties of quark stars within the confined-isospin-density-dependent-mass model. In future, it will be interesting to see how the present results change if other quark mat-

ter models are used, and how the isovector properties of quark matter, especially the quark matter symmetry energy, will affect other issues such as the quark-hadron phase transition at finite isospin density, the partonic dynamics in high energy HIC's induced by neutron-rich nuclei, and so on. These works are in progress.

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